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APPLICATION OF ATMOSPHERIC ELECTRICAL INSTRUMENTATION FOR DETEC--ETC(U)

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APPLICATION OF ATMOSPHERIC ELECTRICAL INSTRUMENTATION FOR DETECTION OF AEROSOL PLUMES AND ATMOSPHERIC SCRUCTURE

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S/C 391 366

This report summarizes work done under Contract N00019-77-C-0372 for the Naval Air Systems Command. The basic objective has been to compare in-situ measurements of aerosol plumes with atmospheric electrical records in order to evaluate the potential of the latter. Initial efforts involved securing and installing an integrating nephelometer (Meteorology Research Inc. Model 1550B) in the Bellanca atmospheric research aircraft. Subsequently a pilot experiment was conducted to compare nephelometer measurements with atmospheric electrical records obtained simultaneously.

The nephelometer is sensitive to aerosols in the 0.1 to 2 μm diameter size range. In general there are three peaks in the distribution of atmospheric aerosols;

(1) The 'coarse' mode; mechanically generated particles such as dust in the 5 to 10 μm size range, micrometers

(2) The 'accumulation' mode: typically formed by combustion processes, these grow to 0.5 to 1.0 μm micrometers and are optimally sized for measurement with a light scattering device such as the integrating nephelometer,

(3) The 'fresh" mode: also formed from combustion, these are in the 0.01 to 0.1 μm micrometers size range. They grow rapidly by coagulation and agglomeration into the accumulation mode typically in a few minutes up to a maximum of 20 minutes.

Thus the nephelometer is an appropriate instrument to measure the combustion generated aerosols of interest to this NAVAIR program. It measures the light extinction coefficient (b_{scat}) and relates this directly to visibility and particulate mass concentration (gm/m^3). The nephelometer has a visibility

sensitivity from infinity to 1 km--equivalent to a mass concentration of 0 to 3800 $\mu gm/m^3$.

The paper included as an appendix to this report presents the theory of atmospheric electrical measurement of plumes and atmospheric structure which regulates aerosol distribution. Two sets of measurements are discussed. In the Florida measurements it was demonstrated that the atmospheric electrical sensors had greater sensitivity than the light scattering instrument (nephelometer). In that instance, the plume remained intact for a long distance illustrating the importance of atmospheric structure in controlling the fate of aerosol plumes. In this case a low and strong inversion inhibited turbulent mixing and trapped the plume which was carried far downwind by the wind without much lateral dispersion. The atmospheric electrical instruments were able to detect the plume out to 90 km downwind of the source.

In the second set of measurements, made relatively close to a smokestack producing a diffuse plume, the atmospheric electrical sensing proved valuable by locating the plume remotely so that it could be flown through for in-situ measurements with the nephelometer.

Funding under this contract was such that the nephelometer could be purchased, installed and only flown for a few hours. The remainder of the contract funding has been used to attend the conference in Monterey and to write reports.

In the future we hope to continue this investigation and attempt to calibrate the atmospheric electrical measures with nephelometer data to see if the atmospheric electrical parameters by themselves can give reliable quantitative measures of aerosol loading. Assuming a specific pyrotechnic device emits an aerosol cloud with a predictable size spectrum, this should be possible. We also hope to investigate the diffusion and distribution of aerosol clouds as a function of atmospheric turbulence and stability. The Bellanca aircraft has been instrumented with unique turbulence measuring devices for an ongoing cooperative program with colleagues at the Naval Postgraduate School, Monterey.

A P P E N D I X

APPLICATION OF ATMOSPHERIC ELECTRICAL INSTRUMENTATION FOR DETECTION OF AEROSOL PLUMES AND ATMOSPHERIC STRUCTURE

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1. INTRODUCTION

Atmospheric electricity is generally not considered as part of air pollution meteorology. A current summary of instrumentation suitable for remote sensing of aerosols and meteorological factors controlling their distribution (Beran and Hall, 1974) fails to mention atmospheric electrical techniques. However, such measurements provide very sensitive yet simple means for both in-situ and remote sensing of aerosol plumes and of the total boundary layer aerosol loading. This paper describes the concepts and uses of atmospheric electrical measurements as applied to the study of plumes and presents some data acquired with atmospheric electrical sensors along with conventional aerosol measurements for comparison. The first set of measurements were obtained during a field program at Clearwater, Florida, in February 1977 (Durham, *et al*., 1977). Subsequently a second set of measurements was obtained near a stack on Cape Cod during October 1977. The electrical measurements were made as a preliminary test of the technique. These data are used to illustrate the concepts and theory presented in this paper.

1.1 Concept

Because a plume coming from a smokestack contains electric charge on its particles, it can be detected remotely through its effect on the atmospheric electric field; because it contains aerosols, it can be detected in-situ both through electric field and conductivity variations in the local air mass. These properties offer certain advantages:

(1) Electric field measurements make possible remote detection of plumes during the day or at night.

(2) Atmospheric electrical instrumentation is relatively light, simple, inexpensive and requires little power compared to more commonly utilized aerosol measuring techniques. These properties make this instrumentation suitable for use on a small airplane, model aircraft or radiosonde balloon, and particularly attractive to low budget programs. For comparison, a Knollenberg aerosol spectrometer costs about $30,000, and a nephelometer costs $5000 while atmospheric electric instruments cost a few hundred dollars.

(3) The instrumentation has sensitivity to plumes that appears in general at least as good as the other more conventional in-situ or remote detection techniques, and under some conditions may be better.

The objective of this report is to illustrate how airborne atmospheric electrical measurements may be useful in studies of aerosols and atmospheric structure which controls aerosol distribution. While this report describes atmospheric electrical detection of industrial plumes, the approach would be equally viable for detection of any aerosol clouds, exhaust tracks from ships and plumes formed by pyrotechnics.

For those unfamiliar with the parameters discussed here, an electric field (or potential gradient) is the voltage difference between two points divided by their separation. Conductivity is the

ability of atmospheric ions to transport charge: essentially the number of elementary charges per unit volume times their mean mobility.

1.2 Background

It has been known for some time that plumes were charged and could be detected through electric field measurements. Lord Kelvin, the pioneer atmospheric electrician, noted electrical effects associated with the steam plume coming from locomotives (Chalmers, 1967). Moore et al. (1962) report detection of industrial plumes with airborne electric field instrumentation. Boeck (personal communication) has made numerous measurements of electric field variations associated with plumes he crossed under with an instrumented van. During the last few years, one of us (RM) has used an aircraft to trace plumes of space charge coming from several sources including the waterfall at Niagara Falls (splashing water creates space charge) and industrial smokestacks. Additional background material is given by Markson in a discussion on "Atmospheric Electrical Air Tracing and Air Mass Determination" to appear in Dolezalek (1978).

A common question is whether all plumes are electrified and suitable for atmospheric electrical detection? From past experience the answer is "yes"; interestingly, charge polarity has always been negative. Boeck (personal communication) and Moore et al. (1962) also report negative plumes. The source of the charge is probably

triboelectric (frictional) charging as the particles go up the stack. In addition, there would be charging by Cottrell precipitators which also introduces negative charge into the plume if the stack is so equipped. However, the plume measured in Florida was detected remotely with the electric field sensor although no electrostatic precipitator was in the stack.

The ability to conveniently charge plumes with electrostatic precipitators suggests the possibility of changing the sign of the charge by reversing the polarity of the d.c. powersupply. This could offer a means for tracing one particular plume in the vicinity of other plumes. However, even if the plume contained no charge, it would be detectable through its effect on conductivity and the associated change in local electric field within the aerosol cloud.

1.3 Approaches

There are two methods for detecting plumes using atmospheric electrical measurements:

- The first is to record the spatial variation of electric field created by the electric charge in the plume. This can be a

large signal easily separated from the naturally occurring background atmospheric electric field. Electric field measurements inherently offer the possibility for remote detection; the plume we report on here could be detected from an airplane 3 km above it immediately downwind of the stack.

- The second is to measure the decrease of conductivity created by a plume. This effect is caused by aerosols absorbing and thus decreasing the mobility of air ions. Since the measurement is in-situ rather than remote, it allows the detection of the actual location of the plume. Conductivity changes affect, in turn, the local vertical electric field, thus it is desirable to record both so the effects can be differentiated.

In addition to the ability to locate plumes remotely, airborne atmospheric electrical measurements, both of fields and conductivity, can be valuable in pollution meteorology because these parameters are controlled by atmospheric structure. For example, electric field and conductivity soundings frequently indicate inversions and other discontinuities in the vertical structure of the atmosphere more clearly than temperature soundings. This characteristic results from the horizontal stratification of aerosols by stability and other meteorological factors. Since the atmospheric electrical measurements respond

directly to aerosol loading, they show the actual location and presence of particulate matter compared to temperature profiles which only indicate the potential for such particles to accumulate at certain heights.

Figure 1 depicts profiles of electric field, conductivity, and temperature obtained from a sounding over the Gulf of Mexico. Between about 1.0 and 1.5 km, there is a layer of aerosols inferred from the decrease in conductivity coincident with an increase in electric field intensity. Such layers, characterized by the above inverse relationship, frequently occur in the upper portion of the atmospheric exchange layer below a temperature inversion such as seen here at 1.5 km. The rapid increase in conductivity and decrease in field intensity ascending through the top of the exchange layer is typically seen in atmospheric electrical soundings (Salgalyn and Faucher, 1955; Markson, 1976). At 350 m, there is a thin layer of aerosol depicted by a sharp decrease in conductivity and increase in electric field. This corresponds to the height where a power plant plume accumulated in a thin layer about 20 km downwind from the stack we were studying. The temperature profile does not depict an inversion at this level. Another layer of aerosol can be seen at 75 m which is the top of a strong temperature inversion layer extending to the sea surface. The large increase in electric field near the sea is caused in part by a layer of positive space charge which is generally found in the lowest 100 m over the ocean (Markson, 1975).

2. THEORY

An electrified plume can be considered as a horizontal line charge, but since it is near the earth's surface the mirror image line charge within the earth must also be considered. Figure 2 depicts the situation and shows the relative variations of the vertical component of the electric field with height in a vertical plane through the plume. The equation describing the field variation is: $E = \rho_{\ell} / 2\pi\epsilon_o \left(\frac{1}{2h+z} + \frac{1}{z}\right)$ where E = electric field intensity (volts/ meter), ρ_{ℓ} = linear charge density (coulombs/meter), h = distance from the plume to the earth (meters), z = perpendicular distance from point of measurement to the line charge (meters), and ϵ_o = dielectric constant of free space (farads/meter).

If one flew above or below a plume measuring vertical electric field intensity, the magnitude would maximize when directly over or under it, but the sign would reverse from above to below. This is illustrated in Figure 3 which gives the theoretical variation of vertical electric field at different altitudes from the surface to 3 km across a negatively charged plume located at 350 m. Up on the vertical axis is the direction of the fair-weather electric field. The above altitudes were selected to match actual measurements made about 1 to 2 km downwind of the stack we investigated. In this figure electric field data are plotted as solid lines for comparison with theoretical values plotted as dashed lines. They match fairly well except near the surface where the

enhanced reversed electric field intensity signifies that the negatively charged plume was not confined to a thin layer at 350 m but some of it extended downward to near the sea. In the format of this figure it is hard to depict the signal at the higher altitudes; but plotting the data on a different scale (Fig. 4), one can see that the signal rises above the baseline value at a height of 3 km slightly downwind of the stack.

In Fig. 3, while the main part of the plume was placed at 350 m, we also depict a vertical elliptical distribution of less dense aerosol from 750 m to 150 m. This is because the conductivity measurements indicated an aerosol cloud was encountered between these altitudes at times when an unmistakable plume signal could be seen in the electric field record.

Electric field signals indicating plume crossings must be detected above the noise resulting from naturally occurring fluctuations of the fair-weather electric field. Normally the variation at a fixed location near the earth's surface is on the order of 10 to 20 percent in a minute interval. At higher altitudes above the exchange layer the variations are much smaller because there is less convection and less space charge.

The atmospheric electrical global circuit will be briefly described as it is responsible for the fair-weather electric field. For details of its origin and variations see Chalmers (1967) and Markson

(1975, 1976). For purposes of this discussion it suffices to say that the fair-weather field is present in the over 99 percent of the earth's surface away from thunderstorms and local sources of electrification such as blowing sand. The sum of world-wide thunderstorm activity is the generator supporting the fair-weather conduction current and resultant atmospheric electric field as seen in Fig. 5. Note that the conduction current and fair-weather electric field are vertical and this is why the variation of conductivity within an aerosol cloud affects the vertical electric field. Electric field and conductivity are inversely proportional and the conduction current is constant through the atmosphere according to the equation $J = E\lambda$; where: J = the air-earth conduction current (amps/meter^2), E = electric field intensity (volts/meter), and λ = conductivity (ohm-meter)$^{-1}$. In order for the conduction current to remain constant the electric field adjusts to changes in local conductivity; e.g., a decrease in conductivity such as occurs descending through the inversion at the top of the exchange layer, or entering a plume, causes a corresponding increase in electric field.

For this reason an aerosol cloud can be located by a simultaneous increase in vertical electric field and decrease in conductivity. Both the remote (space charge produced) and local (conductivity produced) effects are summarized in Fig. 6. This idealized diagram depicts the expected effects on vertical electric field if measurements were made

from an aircraft flying across a negatively charged plume at varying altitudes. The dashed lines show flight paths and the solid lines the expected corresponding variations of vertical electric field. Passes 1 through 3 descending toward the plume depict increases in field intensity when crossing the plume with excursions from baseline values becoming larger as the measurement is made closer to the charge. The positive (upward) deviations are set to be of the same sign as the fair-weather field produced by a negatively charge earth and positive charge in the atmosphere. The notation $E(\sigma)$ on these lines shows that the electric field variation, E, is only a function of the monopolar space charge (σ) in the plume. Pass 4, through the top of the plume, suggests that at the edge of a cloud of space charge, the electric field maximizes, however by passing through the edge of the plume the conductivity (λ) variation also influences the electric field. On the pass through the center of the plume, Pass 5, the electric field is only affected by the conductivity since the electric field at the center of a uniform cloud of space charge is zero (neglecting the mirror image). Note that this increase is in the sense of the fair-weather field. Pass 6, through the bottom of the plume shows that both space charge and conductivity influence the measurement, but here the negative space charge center being above the point of measurement causes a reversal of the field direction from the fair-weather field. Thus, at some altitude below the plume center, the

space charge and conductivity effects cancel each other as suggested by Pass 6. Below the plume in Passes 7 and 8, the electric field variation is only caused by space charge in the plume; it is in the opposite direction from the fair-weather field, and the effect decreases with increasing separation from the charged plume.

Since charge will leak off plume particles by conduction to the surrounding atmosphere, the capability for remote detection through electric field sensing will decrease with time and distance from the plume's source. The 1/e electrical relaxation time, the time it would take for 63% of the charge to leak off a conductor, is about 15 to 20 minutes in clear air within the planetary boundary layer. The in-situ electric field and conductivity detection capability will remain as long as there is a plume of aerosols even if all the charge has leaked off.

3. INSTRUMENTATION

3.1 Atmospheric electric fields can be measured from an aircraft with electrostatic field mills (Kasemir, 1965) or an electrometer/radioactive probe system (Markson, 1974; 1976). Since the latter type of instrumentation is more sensitive, smaller, lighter and less power consuming, it is more

suitable for detecting perturbations in the fair-weather electric field from a small aircraft. The atmospheric electrical sensors are mounted on fiberglass wingtip extensions. These are seen in Fig. 7. Potential gradient, the inverse of the electric field, is measured by dividing the voltage difference between the upper and lower probes by the distance between them. A differential electrometer is utilized to make this measurement and the probes must be positioned in the same equipotential surface relative to aircraft charge in order to eliminate the latter from the measurement.

3.2 Conductivity is measured with the Gerdien tube cylindrical capacitor seen in Fig. 7. A voltage is put on the center electrode creating an electric field within the cylinder. Ions drift to the center electrode producing a small current (10^{-10} to 10^{-11} amps) which is measured with an electrometer. Kraakevik (1958) gives details of the airborne conductivity measuring technique.

The aircraft used for the atmospheric electrical measurements is a turbocharged Bellanca modified with wingtip extensions and special turbochargers for atmospheric research above 10 km. It is shown in Fig. 8. Besides the atmospheric electrical instrumentation, it carries meteorological sensors for measuring air temperature, dew point, turbulence (C_t), remote temperature of the earth's surface (IR), the air's refractive index, and altitude. Data are recorded in real time on an 8-channel analog recorder so the flight path can be adjusted in accordance with variations seen in the records.

4. PLUME MEASUREMENTS

The first data discussed were obtained on the morning of 12 February 1977 near Clearwater, Florida, in the plume of a 565 mw oil-fired power plant with no control devices. Two aircraft were used: the Bellanca described earlier and a Cessna 206 operated by Meteorology Research Inc., Altadena, California. The 206 was instrumented to measure SO_2, light scattering coefficient (integrating nephelometer), and aerosol size distribution (aerosol analyzer and optical counter) along with numerous other pollutant, aerosol, and meteorological parameters (see Durham *et al*., 1977; Blumenthal *et al*., 1977). Figure 9 is a map of the sampling region showing the location of the plume and the sampling traverses. Figure 10 shows traces of the SO_2 and light scattering coefficient in the plume at about 40 km downwind of the plant obtained by the 206. The plume is defined well by the SO_2 and less well by the scattering coefficient (b_{scat}). Aerosol size distribution measurements obtained in the plume on this traverse showed that the volume distribution peaked at approximately 0.15 μm diameter*. Since the integrating nephelometer is most sensitive to aerosol in the range 0.1 to 2 μm diameter, and the aerosol in this plume was at the bottom of this range, it was not surprising that the nephelometer was only a mediocre indicator of the plume.

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* The volume distribution is a plot of $\frac{dv}{dD_p}$ vs. D_p, where D_p is aerosol diameter and v is aerosol volume/m^3 of air. See Whitby *et al*., 1976.

Figure 11 shows the electrical parameters obtained by the Bellanca flying in formation with the Cessna 206 at the same altitude on the above pass through the plume. The b_{scat} data obtained by the 206 are plotted for comparison. The electric field (E) and the conductivity (λ) have their normal inverse relationship and are seen to be excellent indicators of the plume aerosol. The electrical measurements indicate a plume width comparable to that shown by the b_{scat} (about 1km).

Similar passes by the Bellanca at the same distance but 30 m higher indicated similar increases in electric field but only a very slight corresponding effect in the conductivity. This suggests that the aircraft was at the top edge of the aerosol cloud. Thus the electrical measurements can be used to indicate what portion of the cloud is being penetrated and whether the bulk of the cloud is above or below.

Figure 12 shows a traverse at 90 km downwind again at 274 m msl. The decrease in conductivity along with the increase in electric field indicates that the aircraft was in the plume. By this distance much of the original charge should have leaked off. The data show that the conductivity effects alone are sufficient to clearly indicate the plume even at far downwind distances.

The second set of measurements were obtained on the afternoon of 29 October 1977 two km downwind of the smokestack near the eastern end of the Cape Cod , Massachusetts, Barge Canal. The Bellanca aircraft had been equipped with an integrating nephelometer (MRI Model 1550) and this allowed direct measurements of particles to be made simultaneously with the atmospheric electric field measurments from a single aircraft platform for comparison. Figure 13 presents the results of these measurements recorded as the aircraft flew back and forth across the plume at varying heights. The same type of electric field signatures (solid line) as observed during the Florida experiment were recorded with a reversal of sign from above to below the plume. The signal sensed by the nephelometer (dashed line) was difficult to detect and of short duration lasting only a few seconds. It was detected only through a height increment of 150 m while the electric field signal could be observed from as low as the aircraft could safely fly to more than 1 km above the plume. One advantage of the electric field instrumentation was illustrated during this experiment. We had trouble locating the invisible plume in order to record the nephelometer signature, but by using the remote detection capability of the electric field instrument it was possible to find the plume for the in-situ measurements. To accomplish this we crossed the plume at various altitudes and observed in what height range the sign of the reversal took place; this marked the plume's position. An obvious application of this technique is to locate plumes at night.

5. CONCLUSIONS

The data presented in this report resulted from preliminary tests of the concept of using atmospheric electrical instrumentation to detect point source aerosol plumes. The results show that the techniques are capable of detecting such plumes in-situ at long distances from the sources as well as detecting them remotely closer to their origin. The electrical measurements have been shown to be more sensitive to aerosol in the 0.1 μm diameter and below range than light scattering instruments. Although other instruments, such as Aitkin nuclei counters, exist which are sensitive below 0.1 μm diameter, the electrical instruments offer the possibility of a much cheaper and simpler detection system. Since the experiment reported here was limited in nature, much more work remains to be done to define the relationship between conductivity and electric field on one hand and aerosol mass and size distribution on the other.

Acknowledgments--Partial support for the work reported here came from the Naval Air Systems Command, Code AIR 310C, Contract No. N00019-77-C-0372.

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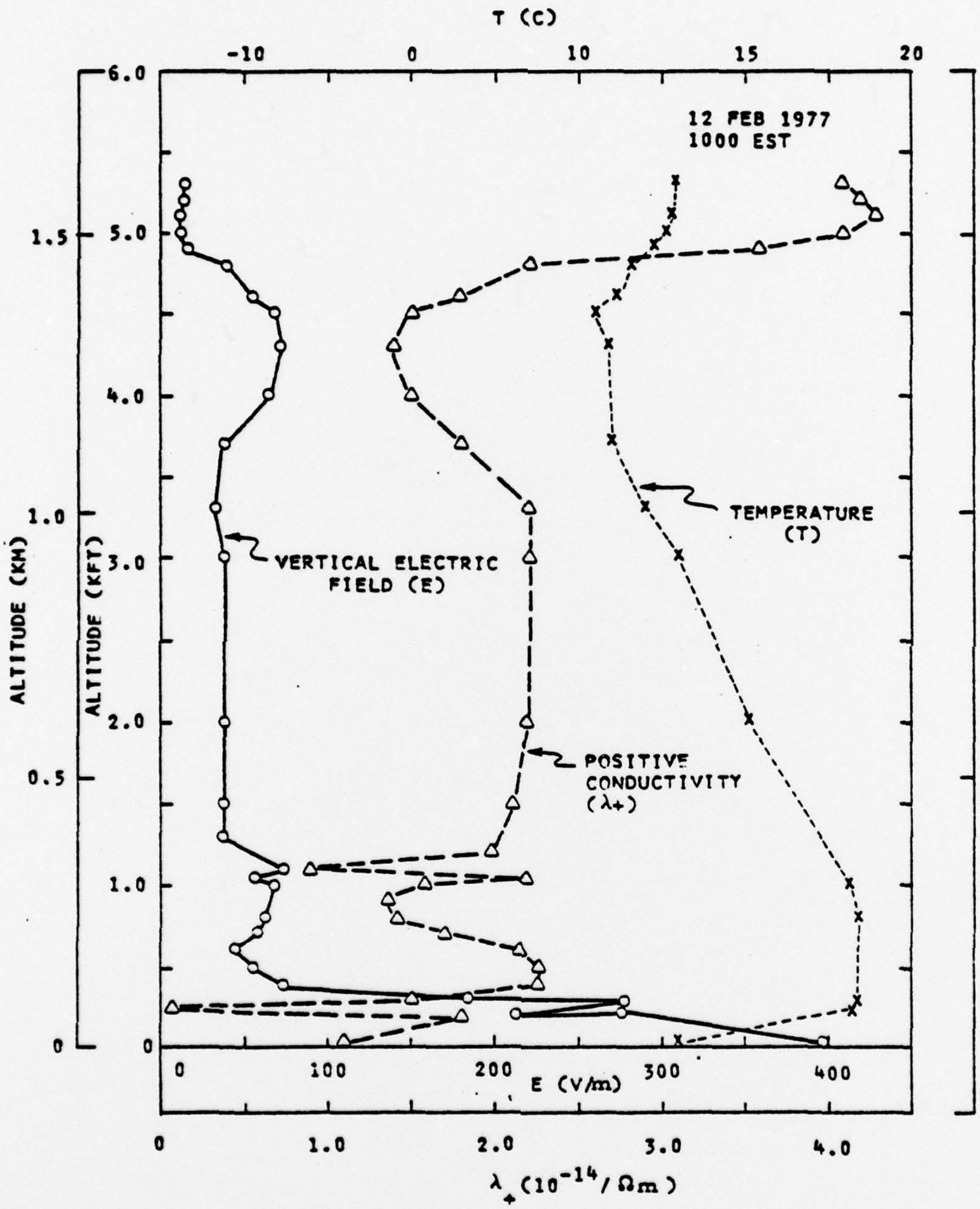

Fig. 1 Soundings showing profiles of vertical electric field, conductivity and temperature obtained about 20 km NNW of a power plant near Clearwater, Fla., on 12 February 1977.

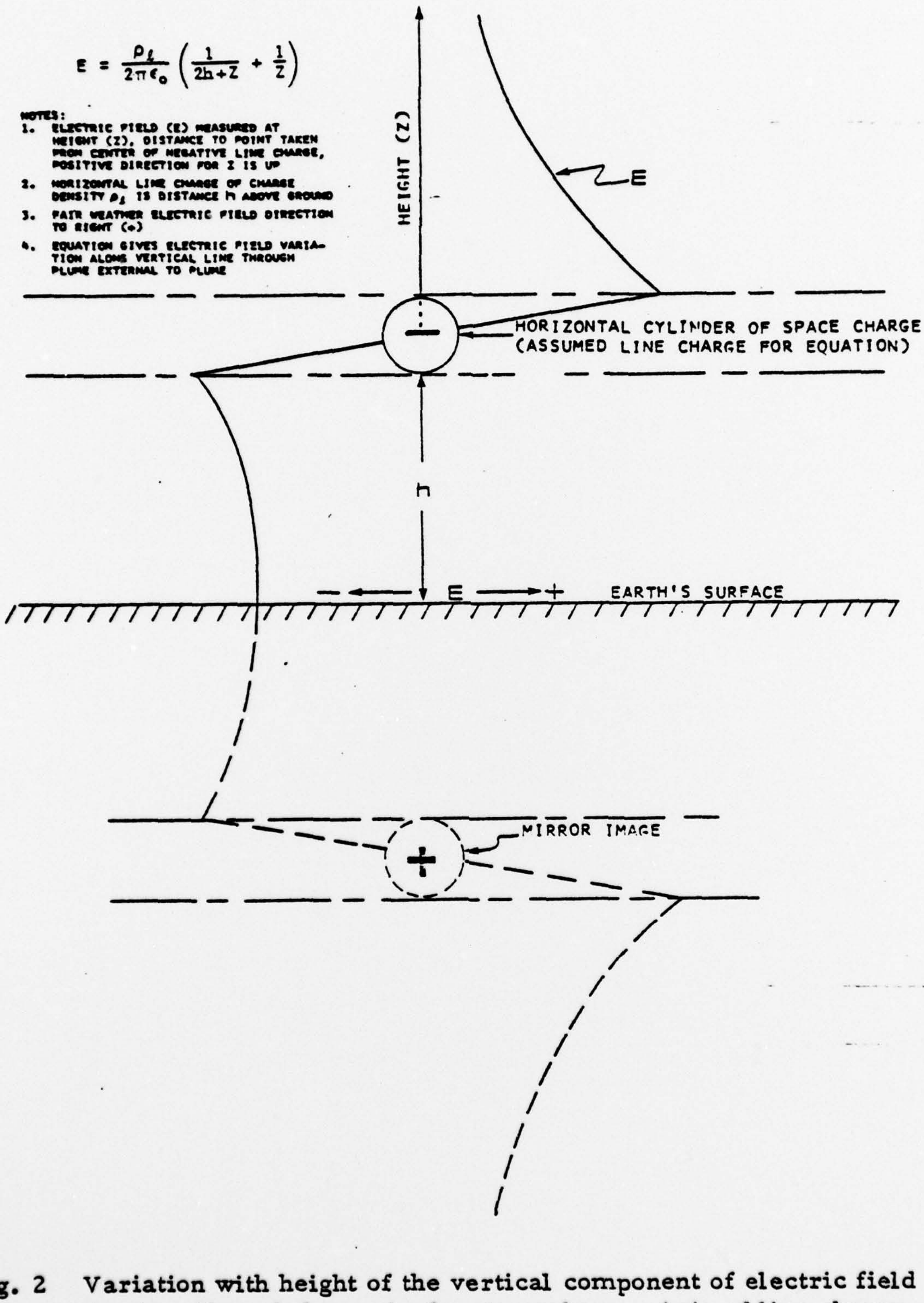

Fig. 2 Variation with height of the vertical component of electric field due to a line of charge in the atmosphere. Axis of line charge is perpendicular to page.

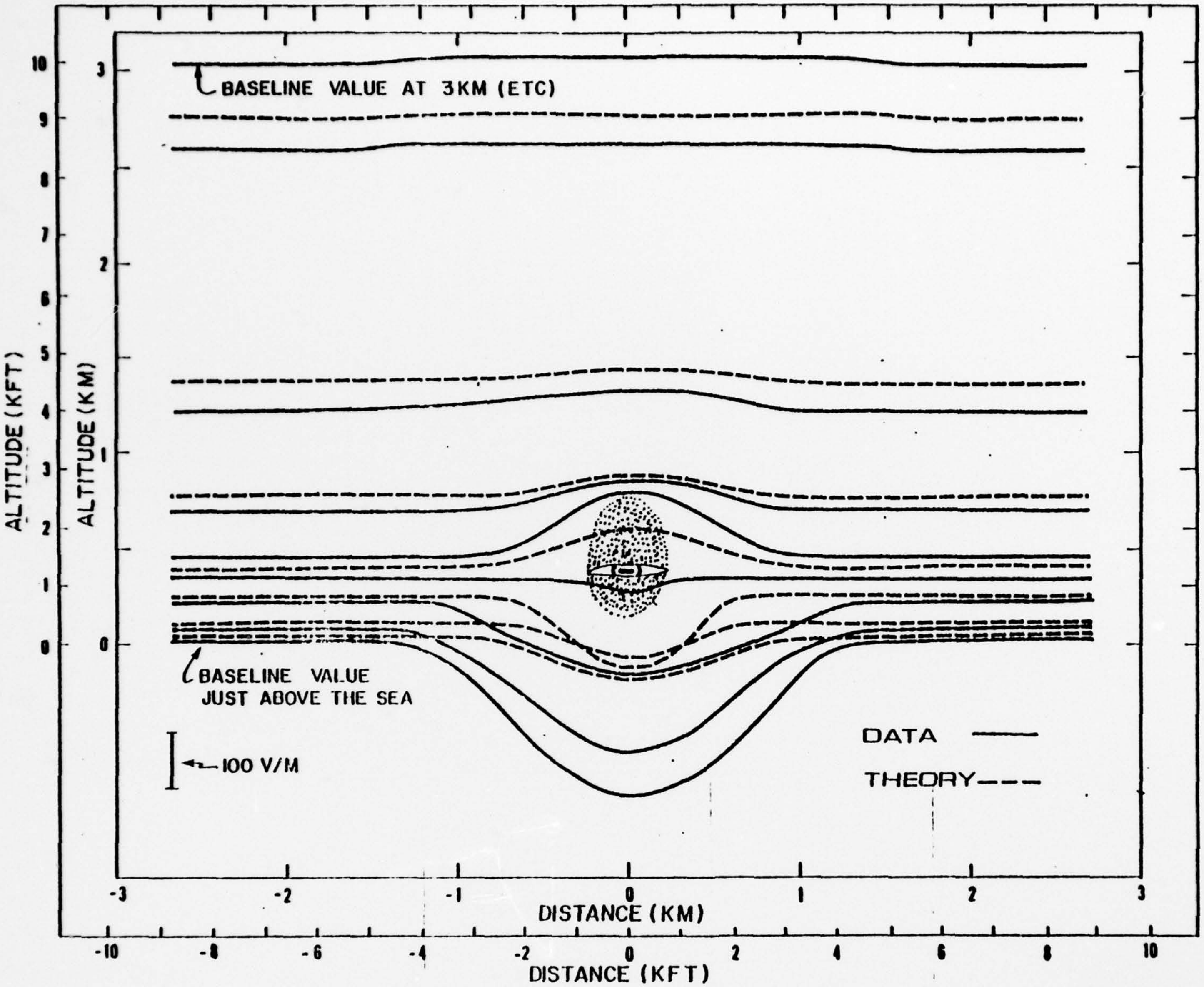

Fig. 3 Comparison between measurements and theory for variation of vertical electric field along horizontal flight paths crossing above, through, and below a negatively charged plume. Axis of plume is perpendicular to page. Near Clearwater, Fla., 12 Feb. 1977.

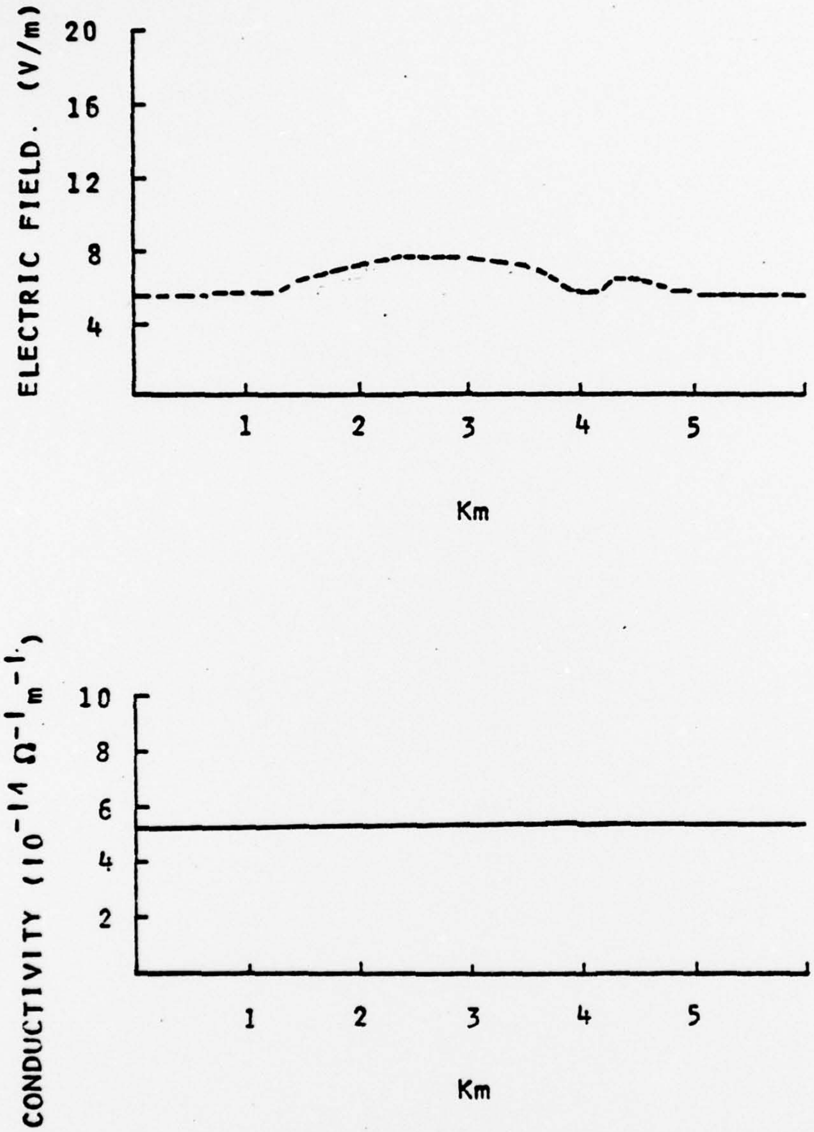

Fig. 4 Variation of vertical electric field crossing an industrial plume at 3 km altitude, 1/2 km downwind of the stack emitting the plume, near Clearwater, Fla., 12 February 1977.

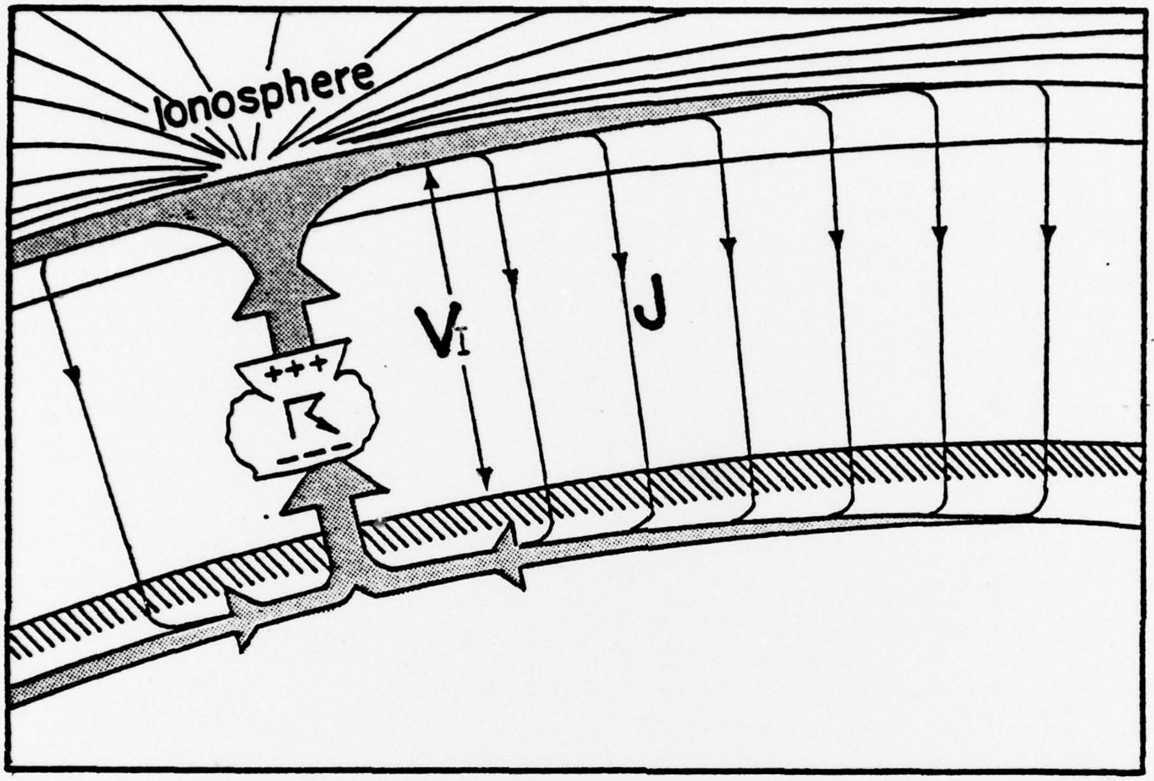

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Fig. 5 The basic elements of the atmospheric electrical global circuit; thunderstorms, the ionospheric potential (V_I), and the fair-weather conduction current (J).

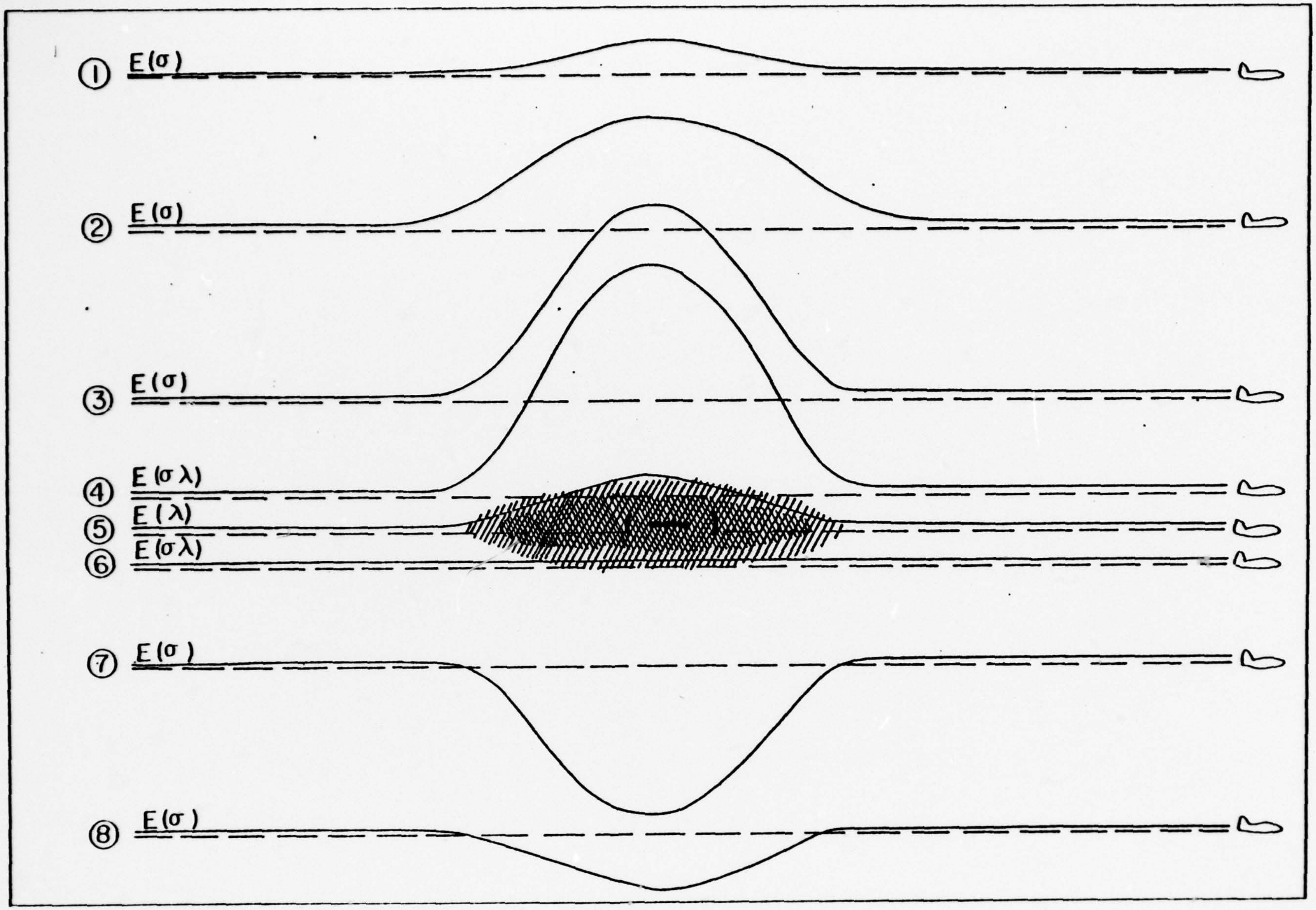

Fig. 6 Idealized variation of vertical electric field along horizontal flight paths crossing above, through, and below a negatively charged plume. The effects of space charge (σ) and conductivity (λ) at different heights are indicated.

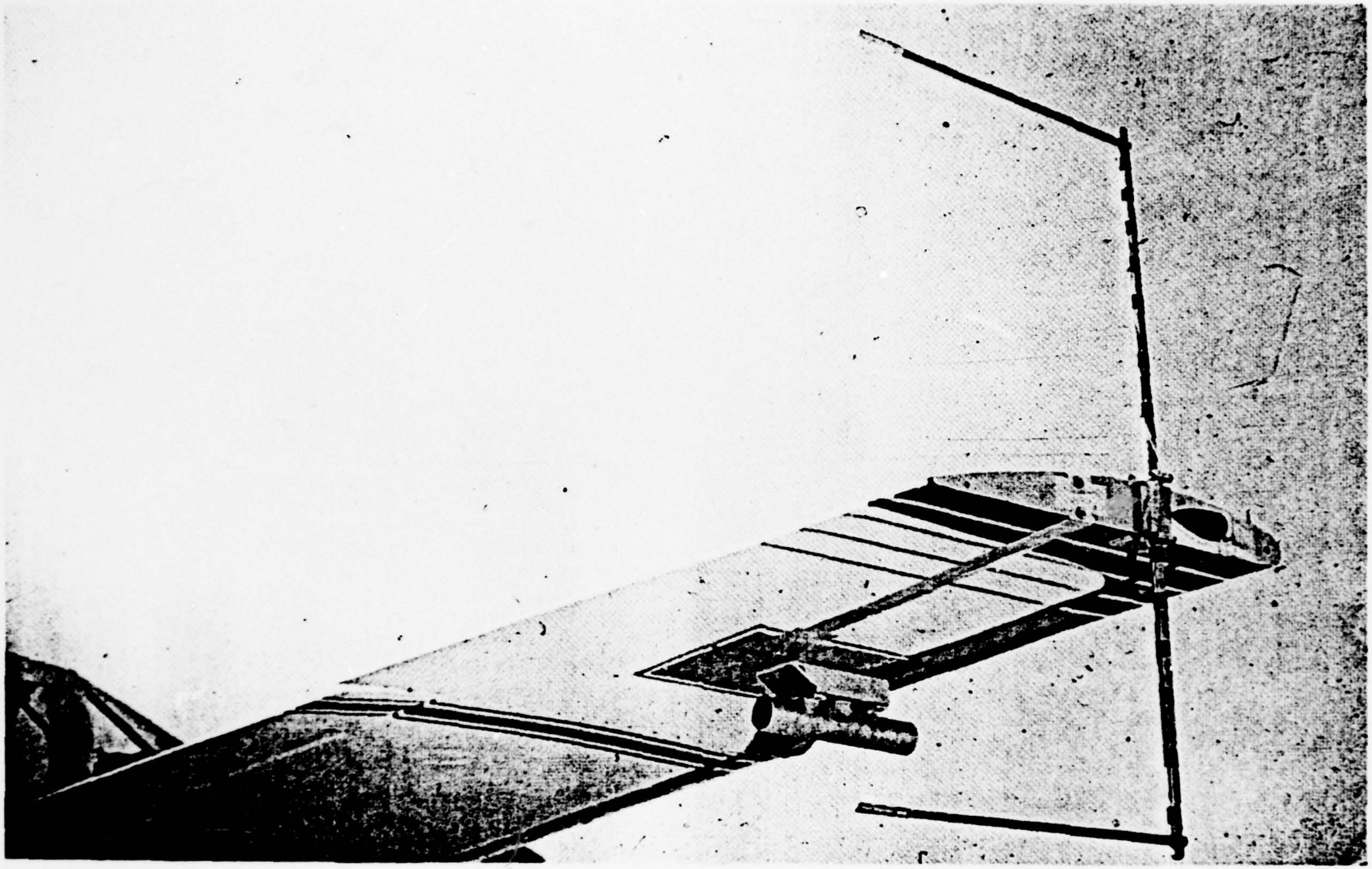

Fig. 7 Wingtip area of aircraft showing vertical potential gradient antenna and conductivity tube.

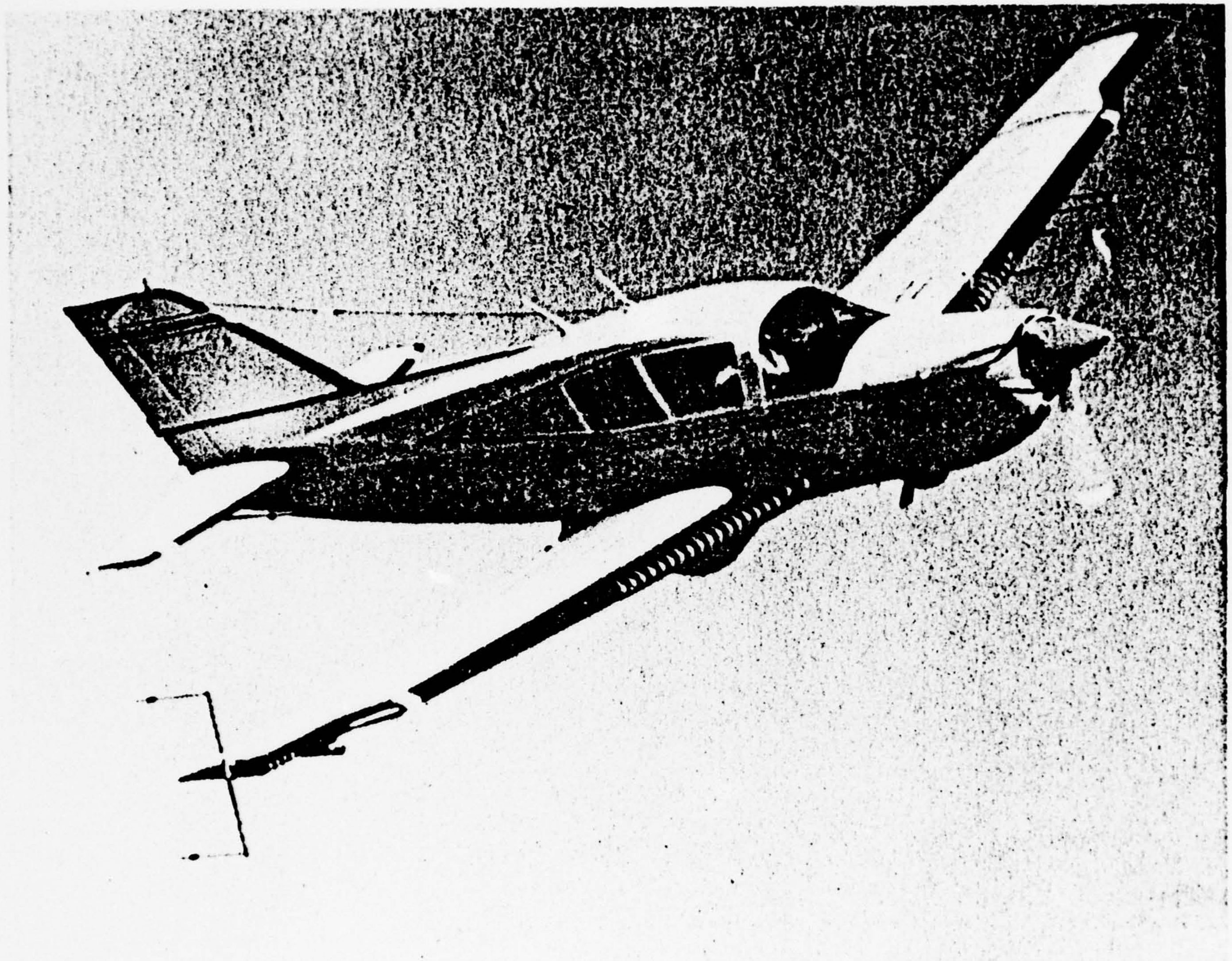

Fig. 8 Bellanca aircraft used for atmospheric electrical research.

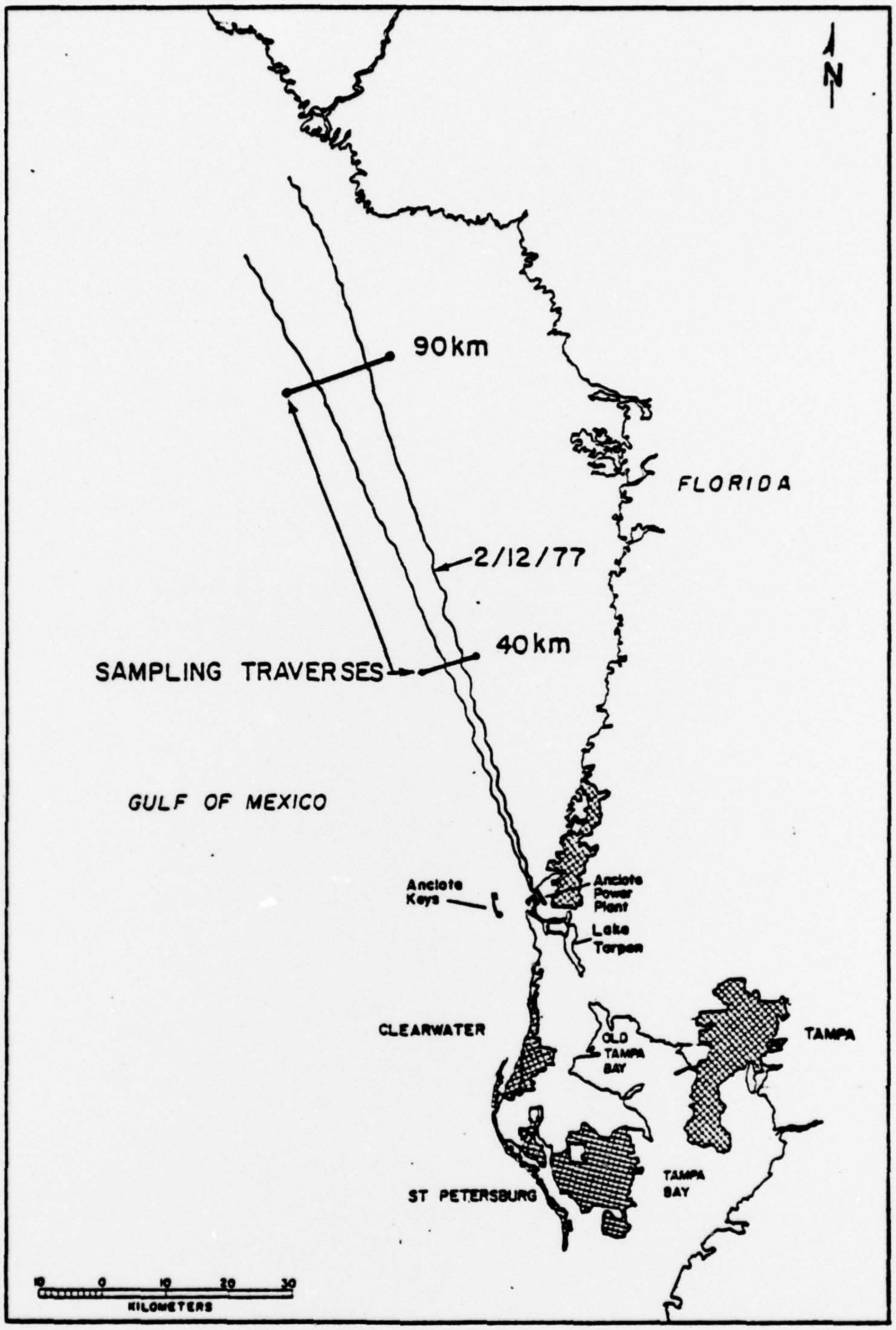

Fig. 9 Traverse Sampling Paths

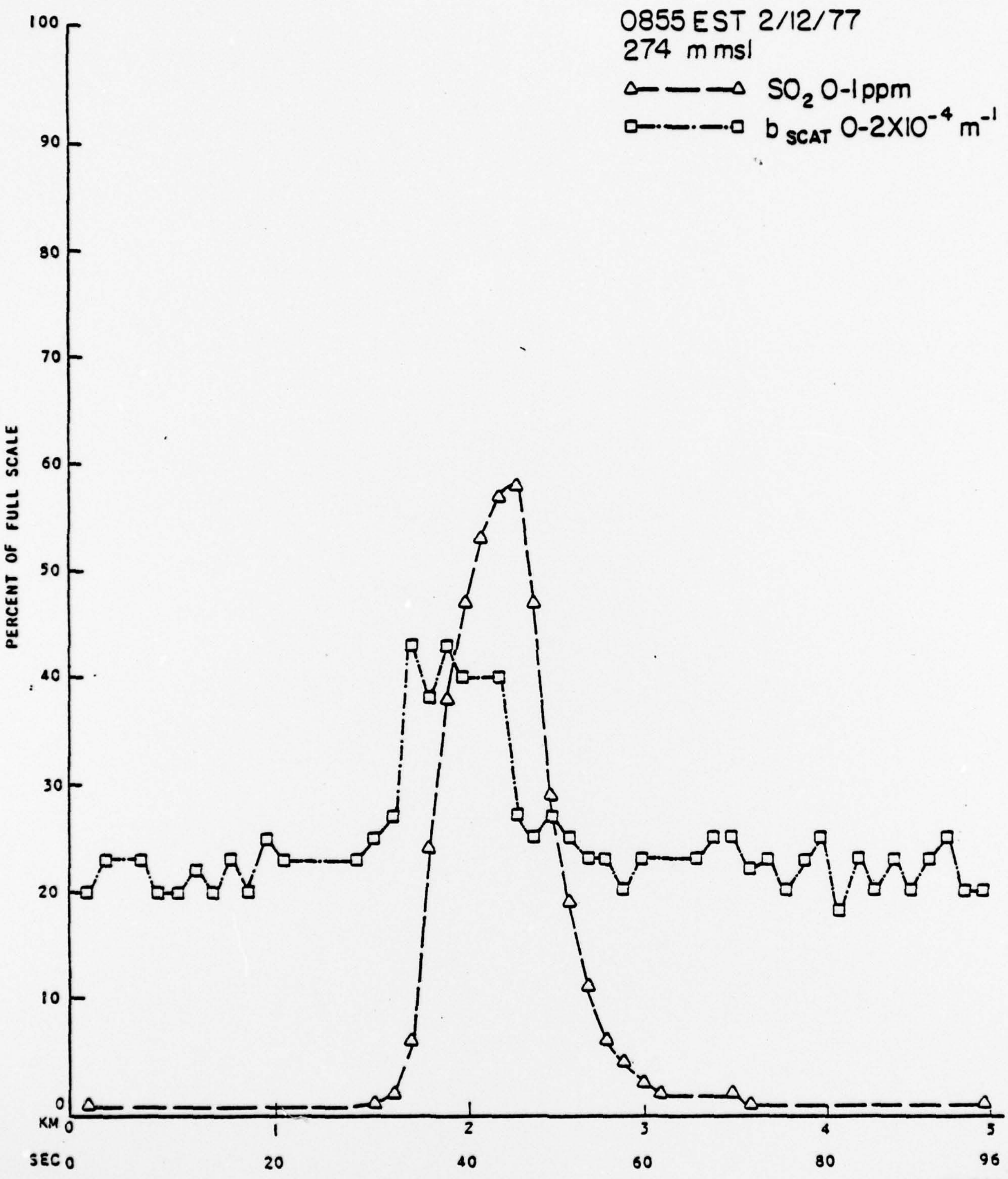

Fig. 10 Horizontal traverse through plume at 40 km downwind (made by 206). (Offset of peaks due to different response times of instruments.)

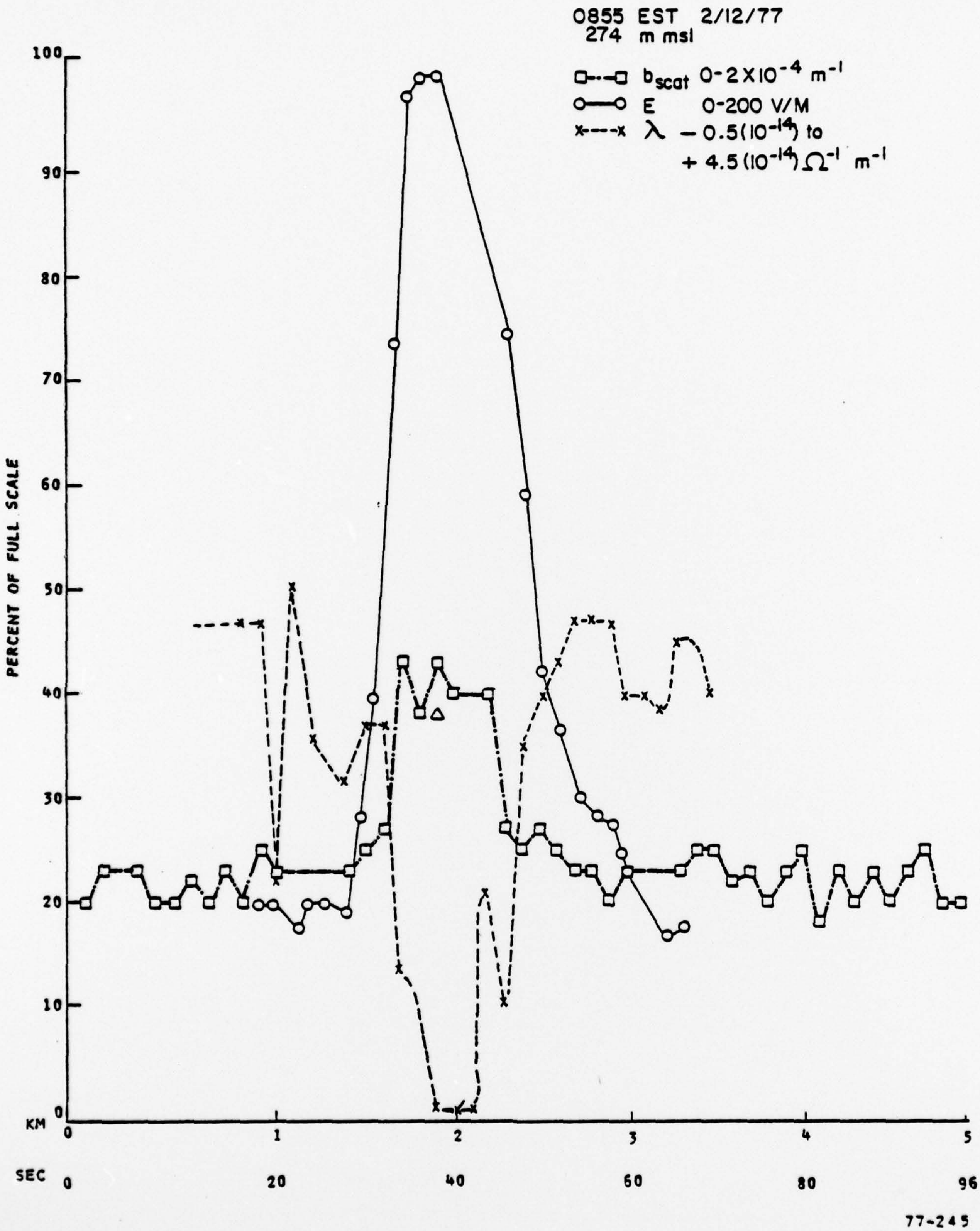

Fig. 11 Horizontal traverses through plume at 40 km downwind. (Data from formation flight of 206 and Bellanca showing correlation of aerosol and electrical measurements.)

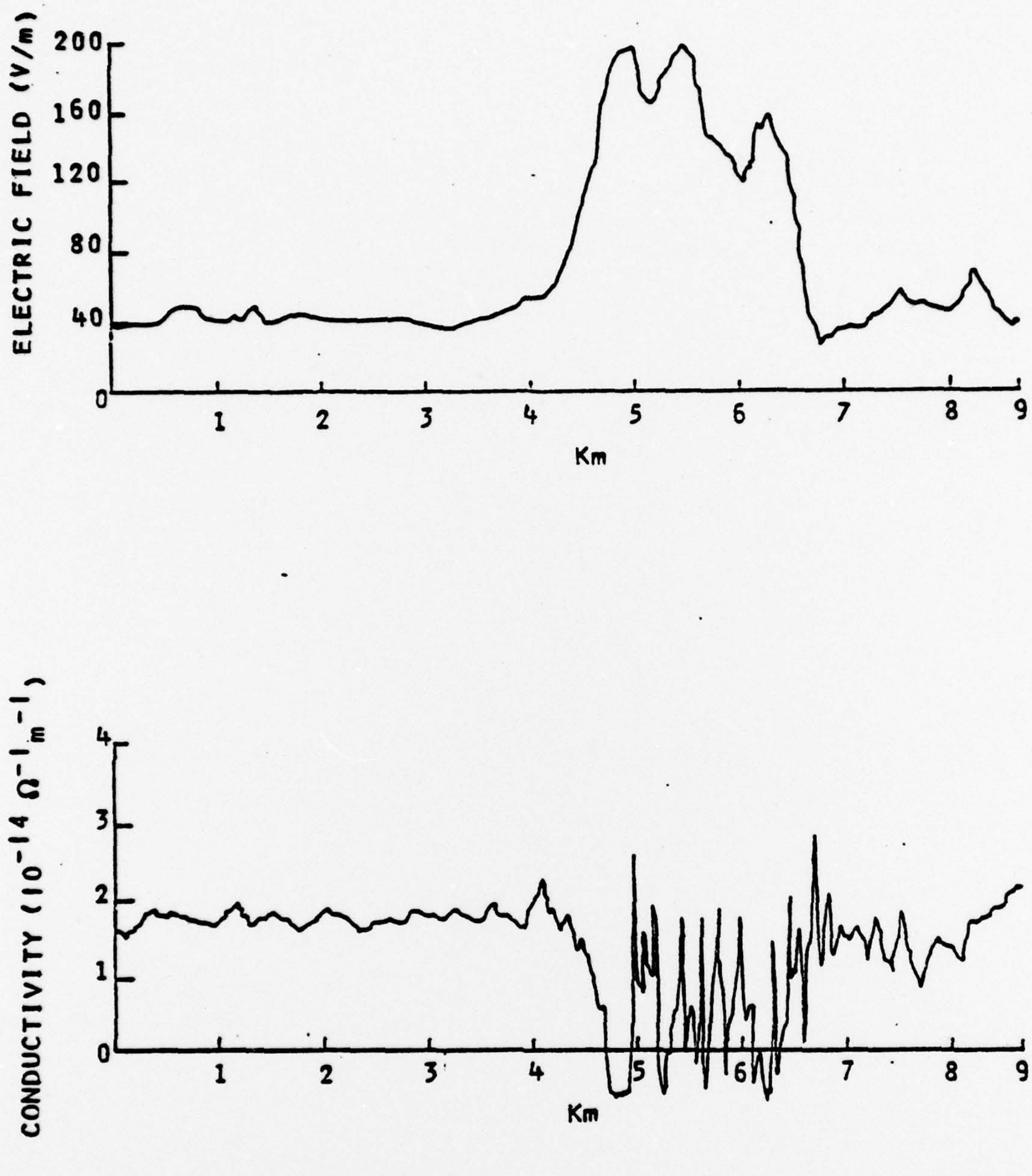

Fig. 12 Electric field and conductivity variations crossing plume 90 km from its source, at 0913 EST, 2/12/77, 274 m msl. The aircraft is near the altitude of the plume center.

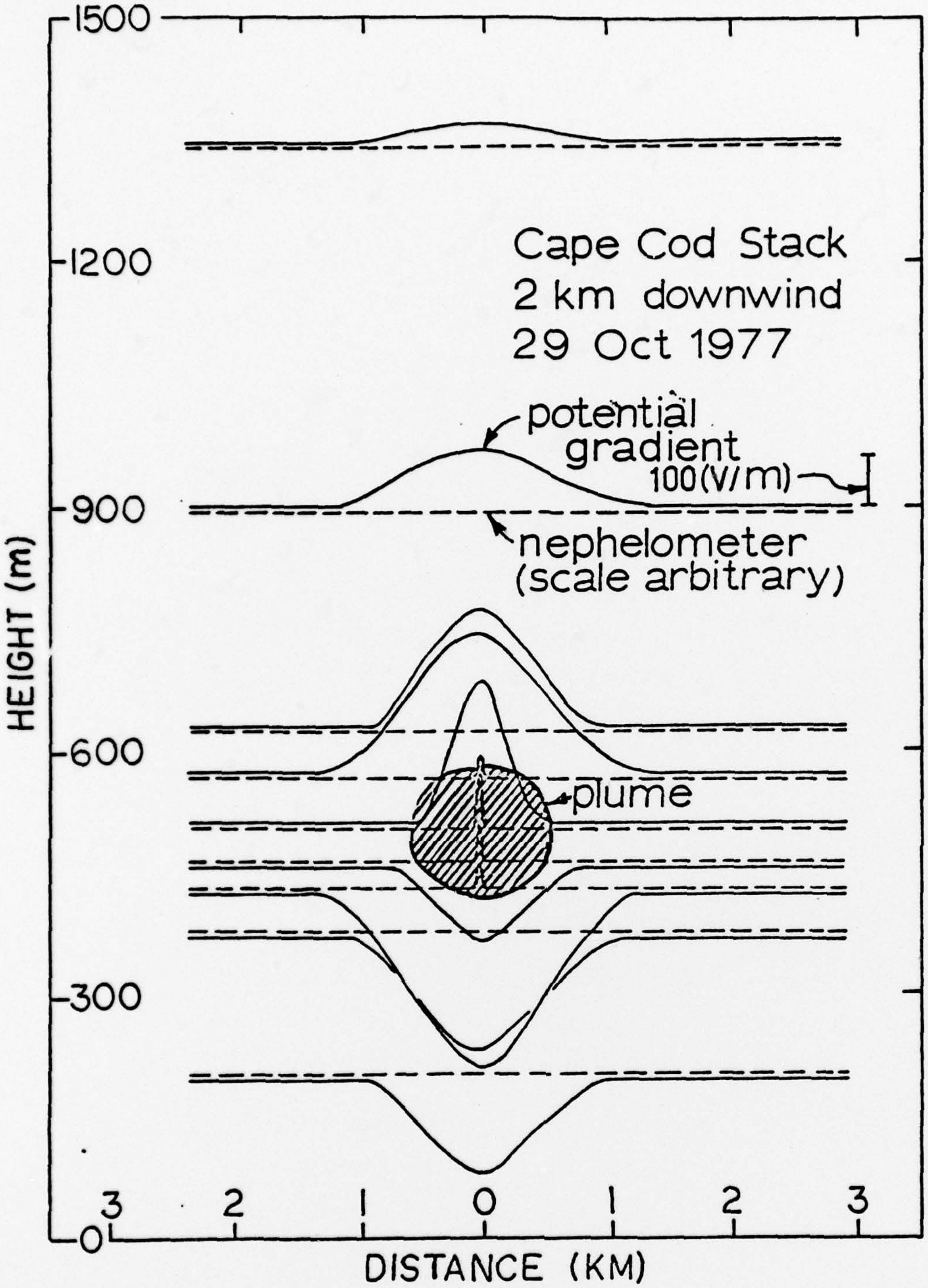

Fig. 13 Variation of vertical electric field (solid line) and scattering coefficient (dashed line) during passes above, through, and below smokestack plume.